1. Introduction

This is first and foremost a book about short term climate *prediction*. The predictions we have in mind are for weather/climate elements (mainly temperature (T) and Precipitation (P)) at lead times larger than two weeks, beyond the realm of detailed Numerical Weather Prediction (NWP), i.e. predictions for the next month and the next seasons out to at most a few years. We call this *short-term climate* so as to distinguish it from long term climate change which is not the main subject of this book. A few decades ago 'short term *climate* prediction' was known as 'long range weather prediction'.[1] In order to understand short-term climate predictions, their skill and what they reveal about the atmosphere, ocean and land, several chapters are devoted to constructing prediction *methods*.

The approach taken is mainly *empirical*, which means literally that it is based in experience. We will use global data sets to represent the climate and weather humanity experienced (and measured!) in the past several decades. The idea is to use these existing data sets in order to construct prediction methods. In doing so we want to acknowledge that every measurement (with error bars) is a monument about the workings of nature. We thought about using the word statistical instead of empirical in the title of the book. These two notions have overlap obviously, but we prefer the word empirical because we are driven more by intuition than by a desire to apply existing or developing new statistical theory.

While constructing prediction methods we want to discover to the extent possible how the physical system works from observations. While not mentioned in the title *diagnostics* of the physical system will thus be an important part of the book as well. We use a variety of classical tools to diagnose the geophysical system. Some of these tools have been developed further and/or old tools are applied in novel ways. We do not intend to cover all diagnostics methods, only those

[1] The distinction between weather and *climate* prediction is roughly along the lines of deterministic vs probabilistic. As long as forecasts are presented deterministically in the short range the term weather prediction is used. The larger uncertainty makes presentation of longer lead prediction probabilistic, more or less by necessity, hence climate prediction. More on this in Ch9.6

that relate closely to prediction.

There will be an emphasis on *methods* used in operational prediction. It is quite difficult to gain a comprehensive idea from existing literature about methods used in operational short-term climate prediction. There are many articles on any one method in a research environment. Very little gets written about operational methods and activities. The emphasis on empiricism is also unusual. Many (review or research) articles have been written in the last two decades on seasonal prediction by the extension of NWP technology to climate (for instance: Shukla et al 2000). Overview articles rarely described empirical methods, an exception being a brief overview by Hastenrath(2003). Empirical methods have not only survived, they have been further developed. This book should fill some of the gaps.

There are no particular geographical limitations in this book. Most methods discussed would potentially be applicable anywhere on the planet, even if the examples given are somewhat biased towards the experience in the United States. As much as possible we have included examples and illustrations for the often overlooked Southern Hemisphere. The difference between the hemispheres is striking and especially helpful when one wants to know how the system works. Nature has two experiments going on simultaneously in the two hemispheres with somewhat different settings.

Where we show illustrations, while we do refer to older literature (and give credit) new calculations were made in virtually all instances, using the 1948-present global NCEP/NCAR CDAS-Reanalysis (Kalnay et al 1996; Kistler et al 2001). This data set includes many variables (wind, pressure, temperature) at many levels in the atmosphere, but also global sea surface temperature (SST) and is kept up to date. Over land we use soil moisture (w) generated by running the Huang et al(1996) model. SST and w are thought to be the source of some (if not most) of the memory in the geophysical system leading to short term climate prediction skill. A large number of figures and verification results refer to 500mb height, a traditional choice. This variable, half way up in the atmosphere, has been the subject of extensive diagnostic study and forecast verification since upper air data became available.

In some figures data all the way through 2006 were used. Indeed the author has always felt the confrontation of ideas with the real time experience to be especially appealing.

Although we emphasize the empirical approach there will be plenty of reference to Numerical Weather Prediction (NWP) and its recent extensions into climate modeling. After all the goals are similar, so we will make comparisons and refer to concepts widely known by dynamicists.

Although we emphasize time scales beyond 2 weeks, we will discuss application of empirical methods to time scales shorter than 2 weeks where this is helpful in demonstrating how these methods work. This is especially true for understanding teleconnections. While teleconnections are usually mentioned in short term climate prediction, (like the effect of ENSO on the extratropical winter mean state in the Northern Hemisphere), teleconnections owe their existence to processes operating on a day-by-day instantaneous time scale. There is also the puzzling question why some methods, that have been retired for short range prediction a long time ago, should still be competitive in the longer ranges.

There will be plenty of verification results in many of the chapters, but verification *methods* are not the subject of this book. Only traditional verification measures, anomaly correlation (AC), root-mean square error (rmse) etc are used. We occasionally mention a notion called cross-validation (CV) which applies to situations when retroactively made forecasts need to be verified. CV means that the verification datum is not used in any way when developing the forecast method, so as to ensure its independence as if it was future data (Michaelsen 1987). For recent developments in verification itself, including probability scores, the reader is referred to a book edited by Jolliffe and Stephenson(2003).

The seasonal forecast, regardless of method, has been around a long time. For instance the NWS in the US started experiments in 1958. But even before that, efforts were underway in many countries. Opinions differ as to whether the methods used at that time were an art or a science.

More recently there have been several huge advances in this field that have made the approach more methodical. The first is the steady increase in the size of global data sets, punctuated by global Reanalysis in the mid-nineties which made the data set available to a wide audience. This obviously is the basis for empirical prediction. The second is the recognition of the global ocean as an external memory that could aid seasonal forecasts in the atmosphere - special mention goes to the El Nino-Southern Oscillation phenomenon (ENSO), where redistribution of SST anomalies and tropical convection may impact areas very far away through teleconnections.[2] The third advance is the development of Numerical Methods for climate prediction. This is a natural extension of NWP to short term climate prediction. The fourth major advance is the development of statistical-empirical methods, including an honest assessment of skill by retroactively made forecasts. In view of these recent advances it is perhaps timely to write this book.

The contents of this book are at the intersection of three scientific disciplines. Firstly there is geophysical fluid dynamics, which is the basis for much of modern meteorology and oceanography. Secondly, there is a large dose of statistics - this follows naturally from using large data sets. Thirdly there is applied mathematics because some of the methods are rooted in basic mathematical concepts like eigen analysis, waves, etc.

While utility has driven most of the research in prediction methods, there is also the noble pursuit of knowledge. Not everything mentioned in this book has proven to be practically useful. Whether it could be made useful is not always known ahead of time.

Another element of this book will be an attempt to simplify methods to their bare essentials. There also is a very practical side to the material since the author has been close to the operational forecast for many years.

This book abounds with 'Rock in the Pond' experiments. The proverbial experimental physicist who threw a rock in the pond had plenty to think about before he/she could explain the

[2]Before ENSO was a hot topic, Jerome Namias, grandfather of long-range prediction in the US was a lone voice pushing the state of the ocean as predictor for the atmosphere.

ripples emanating from the place of impact, reflections from the boundary etc. Our typical experiment is to place an idealized disturbance of specified diameter at a certain location in a physical setting and wonder what will happen next.

The nine remaining chapters are organized as follows. In Chapter 2 we have collected some of the mathematics and statistics that underly the rest of the book and is specifically used. Chapter 3 presents a forecast method called Empirical Wave Propagation (EWP). Given a large data set EWP can achieve a modest level of forecast skill with exceedingly simple means. Moreover EWP is a basis for understanding teleconnections as per wave propagation on the sphere. Chapter 4 deals with one-point teleconnections in the atmosphere. While teleconnections are not predictions as such, they describe the mechanism that makes, for instance, ENSO relevant to the mid-latitudes. A variant, empirical orthogonalized teleconnections (EOT), leads naturally to the subject of Chapter 5 which deals with empirical bi-orthogonal functions (EOFs), which are the cornerstone of a majority of modern empirical prediction methods. Use of EOFs for diagnostic purposes is also exceedingly common these days. Chapter 6 is a brief discussion of estimates of the degrees of freedom in the atmosphere - how many processes appear to be going on independently?. As is Chapter 3 (EWP), Chapter 7 on analogues is an account of a method pioneered by the author. While natural analogues fail in most circumstances (of practical prediction interest) the constructed analogue (CA) is presented as a solution for the lack of data one would need for natural analogues to be a success. CA can be used for many different purposes, we discuss prediction of global SST, specification of fields of one variable from another, calculating (by empirical means) the fastest growing modes etc. Chapter 8 gives a list plus discussion of nearly all methods used in modern short-term climate prediction plus examples of most methods. The list includes more than 90% of methods used operationally in the US. There is also an attempt to list, but with less detail, other methods that have been mentioned in the literature, and a discussion about the consolidation of a multitude of different forecasts. Chapter 9 is a look in the kitchen as to how the seasonal forecast is made in practice, including issues that relate to protocol, assumptions as to what users want and understand, managerial attitudes etc. Chapter 10 is a wrap-up and conclusion including an attempt to explain why NWP, when applied to short-term climate prediction, is not necessarily better than a simple empirical method.

Most chapters can be read largely in isolation. Some reviewers suggested to place Chapter 3 (EWP) after Chapters 4 and 5. The reader can change the order of those chapters with only minimal problems. Experienced researchers may jump immediately to Chapter 8 since it comes closest to the contents promised in the title of the book.

With the appearance of a new book, one wonders which previous texts to compare to. Teleconnections and EOFs (our Ch 4 and 5) have been treated in several other good textbooks over the past years. Books by Wilks(1995;2005) and von Storch and Zwiers(1999) are obvious recent references on EOF in Meteorology, while Jolliffe (2002) reaches across many disciplines. Peixoto and Oort(1992), while covering EOF and teleconnections as well, would be a recommended text for diagnostics (or General Circulation Statistics as it used to be called) in general. For most other chapters there are no recent textbooks.

The level of the book varies by chapter but is not basic, i.e. the accessability for complete outsiders and undergraduates is limited. It is a book for graduate students, interested researchers and practitioners in short-term climate prediction. Chapter 9 and some of chapter 8 are easier to read. There is little rigorous derivation. Rather, we apply dynamics, statistics and mathematics in intuitive ways, assuming the reader knows already the basics about regression, time series analysis, Rossby waves or solving a linear system of equations etc. Phrased in terms of prerequisites the readers will thus benefit most if they are already familiar with the basics of atmospheric dynamics or oceanography, basic statistics, especially regression and spectral analysis, and linear algebra, especially eigen analysis. It helps to know something about spectral prediction models used in weather prediction.

There are quite a few historical notes in this book. After all this is an old field and there are almost no previous texts. To the extent that NWP will outperform empirical methods at some point in the future the ironic reader may feel the whole book, because of its emphasis on empiricism, is part of writing history. Maybe so. However, assessment (usually no better than belief) about the importance of empirical methods for short term climate prediction in the future differ. In Chapter 10 we critically review the scientific basis for expecting (or not) that numerical methods should outperform empirical methods in the future.

Long ago, 19^{th} century say, it may have seemed to many that nature consists of a sum of exact cycles. This would suggest that observing for a long enough time, followed by discovery of all cycles and preferably a theoretical underpinning of each cycle, would eventually lead to perfect prediction out to infinity. The approach worked more or less for the motion of heavenly bodies, so why not for the atmosphere and ocean?. Today we think of the atmosphere and ocean mainly as chaotic systems, sensitive to many details and with a finite prediction horizon. This has not lessened the need for observations. But the only periodic (and thus infinitely predictable) components in the system, those that are forced, are the daily and annual cycle (mainly heating) and the tides, mainly gravitational (thermal) in the ocean (atmosphere). Studies of predictability, i.e. assessing how good forecasts of the remaining anomalies could be theoretically, indicate a sobering perspective for short-term climate prediction. The reader studying prediction methods in this book or elsewhere should certainly be aware that even under ideal circumstance prediction skill may not be close to perfect. The main hope is to detect those coupled atmosphere-land-atmosphere components that have predictability time scales longer than what the troposphere on its own is thought to possess (a few weeks).